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Abstract. Since the settlement of S. Miguel Island (Azores), in the XV century, several earthquakes caused important human losses and severe damages on the island. Sete Cidades Volcano area, located in the westernmost part of the island, was attained by strong seismic crises of tectonic and volcanic origin and major events reached a maximum historical intensity of IX (European Macroseismic Scale 1998) in this zone.

Aiming to evaluate the impact of a future major earthquakes, a field survey was carried out in ten parishes of Ponta Delgada County, located on the flanks of Sete Cidades volcano and inside it is caldera. A total of 7019 buildings were identified, being 4351 recognized as dwellings. The total number of inhabitants in the studied area is 11429.

In this work, dwellings were classified according to their vulnerability to earthquakes (Classes A to F), using the structure types table of the EMS-98, adapted to the types of constructions made in the Azores. It was concluded that 76% (3306) of the houses belong to Class A, and 17% (740) to Class B, which are the classes of higher vulnerability.

If the area is affected by a seismic event with intensity IX it is estimated, that 57% (2480) to 77% (3350) of the dwellings will partially or totally collapse and 15% (652) to 25% (1088) will need to be rehabilitated. In this scenario, considering the average of inhabitants per house for each parish, 82% (9372) to 92% (10 515) of the population will be affected. The number of deaths, injured and dislodged people will pose severe problems to the civil protection authorities and will cause social and economic disruption in the entire archipelago.

1 Introduction

The Azores archipelago is located in the Atlantic Ocean, between 37°–40° N latitude and 25°–31° W longitude and is formed by nine volcanic islands (Fig. 1).

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The geological setting of the Azores region is dominated by the role of the American, Eurasian and African lithospheric plates fault boundaries (Searle, 1980). The most important tectonic structures recognised in the area are the Mid-Atlantic Ridge and the Terceira Rift (Fig. 2), that correspond to the main source of the seismic and volcanic activity registered in the region (Machado, 1959; Weston, 1964).

S. Miguel is the largest and most populated island of the Azores archipelago and is located in the eastern part of the Terceira Rift. The island is formed by several volcanic edifices placed along a general E-W direction (Fig. 3) and is crossed by NW-SE, NE-SW, WNW-ESE and E-W regional tectonic structures. Sete Cidades Volcano is an active central volcano with a summit caldera and is located in the westernmost part of S. Miguel, occupying an area of about 110 km^2 and representing 15% of the total area of the island and has as highest point the Pico das Éguas, located at SE of caldera hole, with 874 m.

2 Seismic activity

Since the settlement of the archipelago, in the 15th Century, many destructive earthquakes, volcanic eruptions and landslides were responsible for numerous victims and substantial damages. The most destructive earthquake occurred on S. Miguel Island on 22 October 1522, and destroyed the former capital of the Azores, Vila Franca do Campo, located in the south flank of Fogo Volcano. About 5000 people died due to the collapse of houses and the impact of two major landslides triggered by the event (e.g. Silveira, 2002; Marques et al., 2005). More recently, on 9 July 1998, a violent earthquake with is epicentre 7.5 km NE of Faial Island attained a maximum seismic intensity of VIII/IX (MM-56), killing 9 persons and damaging many buildings and infrastructures (Senos et al., 1998).

In historical times, S. Miguel Island was affected by ten major earthquakes (Table 1). Apart from the events related with tectonic activity several important seismic swarms of

Table 1. Earthquakes that affected S. Miguel Island with intensity equal or higher than VII (EMS-98) (adapted from Silveira, 2002). Legend: * seismic swarms associated with volcanic eruptions, + seismic swarms.

Date	Intensity	More affected area	Consequences
22 October 1522	X	Vila Franca do Campo	5000 deaths. Huge destructions.
June 1638*	VI–VII	Várzea	Destruction of some houses.
November–December 1713+	IX	Mosteiros, Ginetes, Candelária	Destruction of houses and churches.
July 1810*	VII–VIII	W part of São Miguel Island	Destruction of towers, facades and roof of churches.
June 1811*	IX	W part of São Miguel Island	Destruction of many houses.
30 October 1848+	VII–VIII	Várzea, Ginetes, Candelária, Feteiras	Collapse of churches towers, partial or total destruction of buildings.
16 April 1852	VIII	Santana	Several deaths.
5 August 1932	VIII	Povoação	Several injuries. 51% dwellings destroyed, 3000 people dislodged.
26 April 1935	VIII–IX	Povoação	1 death. 30% dwellings destroyed.
26 June 1952	VIII	Ribeira Quente	Huge destructions.

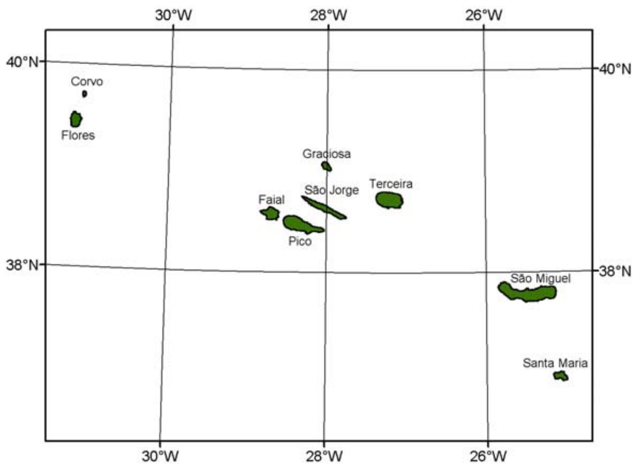

Fig. 1. Geographical location of the Azores archipelago.

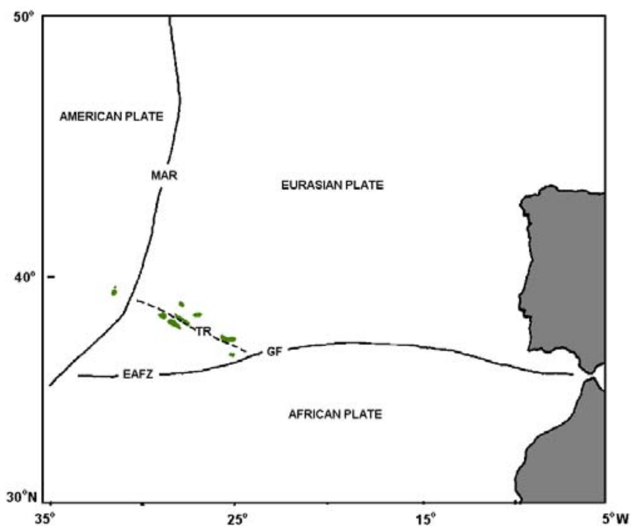

Fig. 2. Main tectonic structures in the Azores region. MAR – Mid-Atlantic Ridge; EAFZ – East Azores Fracture Zone; TR – Terceira Rift; GF – Gloria Fault (Gaspar et al., 1999)

volcanic origin also occurred on the island and in neighbouring submarine volcanic structures. Recent studies (Silveira et al., 2003) concluded that the maximum historical seismic intensity registered on the island was X (EMS-98), as result of the 1522 earthquake (Fig. 4).

In the Sete Cidades Volcano area the maximum historical seismic intensity reached IX (EMS-98) and was related with seismic crises associated to volcanic eruptions that occurred offshore, southwest (1713) and west (1811) of the island (Silveira et al., 2003). In the last 150 years there were no earthquakes with intensity equal or higher than VII, but at least seven earthquakes reached intensity VI (Table 2).

Instrumental seismicity record at the Azores started in the beginning of the XIX century but due to monitoring network constrains accurate data were not obtained before 1980. Figure 5 shows the epicentre distribution of the best-located events in S. Miguel region for the last 20 years. It is clear that the central part of the island is the most seismically active, corresponding to the graben-like structure that extends between Fogo and Furnas volcanoes (Fig. 3). To the west, also the Sete Cidades volcano presents a significant level of seismic activity on land. All these main active central volcanoes and their related volcano-tectonic structures that extend into sea were the place of major earthquakes and seismic swarms in the past. Events occurring in any of these seismogenic zones can have an important impact in S. Miguel Island, namely in the Sete Cidades region, allowing to conclude that seismic hazard need to be considered during emergency planning and land use planning.

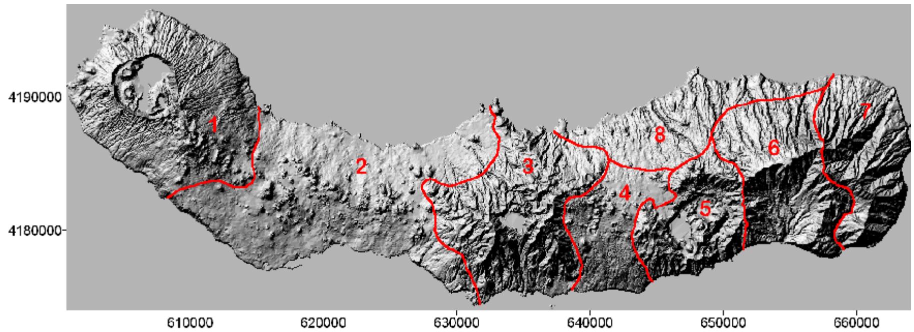

Fig. 3. Main morphological provinces of S. Miguel Island (Zbyszewski, 1961, Wallenstein, 1999): 1 – Sete Cidades Volcano; 2 – Picos Volcanic System; 3 – Fogo Volcano; 4 – Achada das Furnas Volcanic System; 5 – Furnas Volcano; 6 – Povoação Volcano; 7 – Nordeste Volcanic Complex; 8 – North Platform.

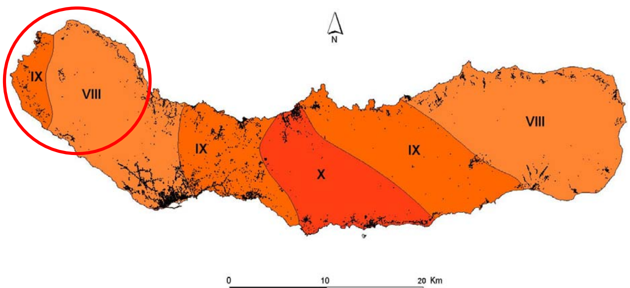

Fig. 4. Maximum historical seismic intensity map (EMS-98) of S. Miguel Island (Silveira et al., 2003). Legend: – study area.

3 Vulnerability analysis

3.1 Field survey

In order to evaluate the impact of a future major earthquake in the study area a detailed field survey was carried out in ten parishes of Ponta Delgada County, located in the flanks of Sete Cidades Volcano and inside it's caldera (Fig. 6). The 7019 buildings existent in the zone were individually visited, being 4351 classified as dwellings (Fig. 7). For each one a data form was filled comprising descriptive information about its geographical location and type of construction (Table 3). Such elements together with a photo from each house were inserted in the Azores Risk Assessment Database – AZORIS, built on a Geographical Information System (Gaspar et al., 2004) for vulnerability analysis.

3.2 Dwellings classification

Each dwelling was classified according to the European Macroseismic Scale 1998, that considers six vulnerability classes (A to F) taking into account a particular type of structure (Table 4). Class A is the most vulnerable and Class F the least vulnerable one (Grünthal, 1998).

In order to apply this classification it was necessary to introduce minor changes in the proposed scheme due to some particularities commonly observed in the Azorean houses. In one way the adobe as a construction material is not used, however the majority of the recent houses are built with blocks of concrete mixed with fine volcanic materials, such as basaltic lava and scoria fragments. Another point that came up during the field survey was related to the observation that several old dwellings had suffered recent interventions, in most of the cases to increase the number of rooms or even floors. For example, it was detected that some dwellings have sections where the external walls are made from lose or weakly cemented stones, while other sections are built with concrete blocks (Figs. 8 and 9). Houses in these conditions were considered to be of class A, due to the different behaviour of the structure in response to a seismic solicitation.

The integration of the collected field data with the EMS-98 vulnerability classes allowed to conclude that around 76% (3306) of the houses belong to class A, 17% (740) to class B, 7% (300) to class C and only 0.1% (5) to class D.

Table 2. Earthquakes that affected Sete Cidades area with intensity equal or higher than V–VI (EMS-98) (Gomes, 2003). Legend: * seismic swarms associated with volcanic eruptions, + seismic swarms.

Date	Intensity
22 October 1522	VIII
June 1638*	VI–VII
November–December 1713+	IX
July 1810*	VII–VIII
June 1811*	IX
30 October 1848+	VII–VIII
16 April 1852	VII–VIII
5 August 1932	V–VI
26 April 1935	V–VI
26 June 1952	V–VI
1 June 1965	V–VI
17 June 1968	VI
21 November 1988	VI
21 July 1999	V–VI

Table 3. Guideline used in the field survey.

Field information	Description	Options
ID_BLD	Identification number for each building	Unique number (1 to n)
ID_GEOGRAPH	Identification string for each parish	Alphanumeric field
STREET	Name of the street where the building is located	Alphanumeric field
AD_NUMBER	House number	Alphanumeric field
TYPE	Use of the building	A – habitacional B – public C – comercial D – monument E – others F – industry
BASEMENT	Presence or absence of basement	Yes or no
FLOORS	Number of floors	Numeric field
ATTIC	Presence or absence of attic	Yes or no
EXT_WALLS_MAT	Type of material used in the construction of the external walls	A – irregular stone without bonding B – bonded stone (cement or adobe) C – bonded stone + plastered walls D – bonded stone + net under + plastered walls E – cement blocks F – wood G – metal H – concrete I – cement blocks + net under J – stone blocks K – stucco
INT_WALLS_MAT	Type of material used in internal walls	A – irregular stone without bonding B – bonded stone (cement or adobe) C – bonded stone + plastered walls D – bonded stone + net under + plastered walls E – cement blocks F – wood G – metal H – concrete I – cement blocks + net under J – stone blocks K – stucco
BASEMENT_PAV	Type of material of the basement pavement	A – wood B – cement C – soil D – stone
GR_FLOOR_PAV	Type of material of the ground floor pavement	A – wood B – cement C – soil D – stone
ID_BLD	Identification number for each building	Unique number (1 to n)
FLOORS_PAV	Type of material of the different floors pavement	A – wood B – cement D – stone
ATTIC_PAV	Type of material of the attic pavement	A - wood B – cement D – stone

Table 3. Continued.

Field information	Description	Options
ROOF_SUPP_MAT	Type of material of the tiles support in the roof	A – wood B – cement C – metal
ROOF_TILES_MAT	Type of tiles used in the roof	A1 – regional clay A2 – mainland clay B – plastic C – metal D – fibro-cement E – isothermal
ROOF_INCL	Roof inclination	A – gentle ($<20^{\circ}$) B – normal (20° to 45°) C – stressed ($>45^{\circ}$)
ROOF_WATER_DS	Type of water drain system from the roof	A – normal A1 – normal + gutter B1 – platband with internal plumbing B2 – platband with external plumbing B3 – platband with gargoyle C – other
WIN_MAT	Type of window material	A – wood B – metal C – plastic
WIN_PROT	Type of window protection	A – without protection B – jalousie C1 – wooden internal jalousie (door shape) C2 – wooden external jalousie (door shape) D1 – metal internal jalousie (door shape) D2 – metal external jalousie (door shape)
DOOR_MAT	Type of door material	A - wood B – metal
DOOR_PROT	Type of protection for door with top or lateral windows	A – wood B – metal
OBS	Additional elements about the building	Alphanumeric field
ID_PHOTO	Identification of the building photo	Alphanumeric field

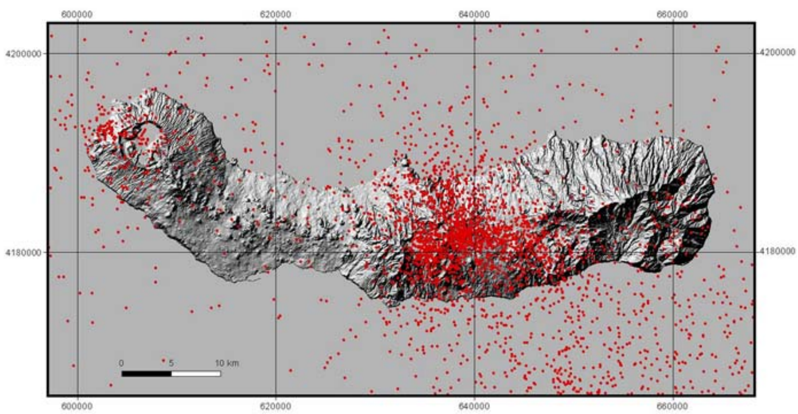

Fig. 5. Map of the seismic activity in S. Miguel Island in the last 20 years (data from SIVISA, 2004).

Table 4. Classification of buildings according to vulnerability (Grünthal, 1998).

	Type of Structure	A	B	C	D	E	F
Masonry	Rubble stone, fieldstone	●					
Masonry	Adobe (earth brick)	●	►				
Masonry	Simple stone	◄	●				
Masonry	Massive stone		◄	●	►		
Masonry	Unreinforced, with manufactured stone units	◄	●	►			
Masonry	Unreinforced, with RC floors		◄	●	►		
Masonry	Reinforced or confined			◄	●	►	
Reinforced Concrete (RC)	Frame without earthquake-resistante desing (ERD)	◄		●	►		
Reinforced Concrete (RC)	Frame with moderate level of ERD		◄		●	►	
Reinforced Concrete (RC)	Frame with high level of ERD			◄		●	►
Reinforced Concrete (RC)	Walls without ERD		◄	●	►		
Reinforced Concrete (RC)	Walls with moderate level of ERD			◄	●	►	
Reinforced Concrete (RC)	Walls with high level of ERD				◄	●	►
Stell	Steel structures			◄		●	►
Wood	Timber structures		◄		●	►	

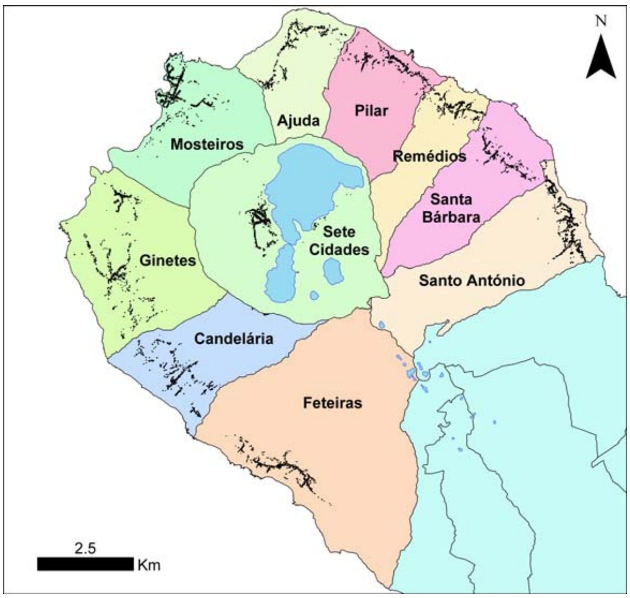

Fig. 6. Location of the ten parishes of Ponta Delgada County considered in this work.

4 Discussion

As it was observed following the 9 July 1998 earthquake, in Faial Island, houses with damages less than 20%, corresponding to grades 1 and 2 of the EMS-98, only needed slight reparations. Dwellings with damages between 20 and 50% (grade 3) were rehabilitated, and new houses were built when the observed damages were higher than 50% (grades 4 and 5).

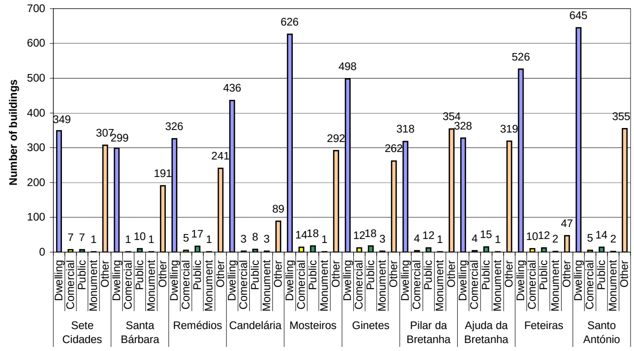

Fig. 7. Number of buildings by type of use in each parish (Gomes, 2003). Legend: A – Dwelling; B – Other; C – Commercial; D – Public; E – Monument.

Fig. 8. Dwelling with external walls in stone and in concrete blocks.

Fig. 9. Dwelling with external walls both in stone and in concrete blocks.

Appling the same criteria to analyse the impact of a future destructive earthquake in Sete Cidades region, and taking into account the type and percentage of damages admitted

Table 5. Calculation of dwellings damages and affected population for different seismic intensity values (EMS-98).

Intensity	Dwellings for each grade of damage								Affected population	
	0		1 and 2		3		4 and 5			
	%	Number	%	Number	%	Number	%	Number	%	Number
V	86 to 100	3741 to 4351	0 to 14	0 to 609	-	-	-	-	-	-
VI	34 to 86	1479 to 3741	14 to 66	609 to 2872	-	-	-	-	-	-
VII	6 to 15	261 to 653	38 to 74	1653 to 3220	11 to 44	479 to 1914	0 to 11	0 to 479	11 to 56	1257 to 6400
VIII	2 to 6	87 to 261	17 to 37	740 to 1610	26 to 45	1131 to 1958	11 to 55	479 to 2393	57 to 81	6515 to 9257
IX	1 to 2	44 to 87	7 to 16	305 to 696	15 to 25	653 to 1088	57 to 77	2480 to 3350	82 to 92	9372 to 10515

Table 6. Present-day dwellings damages and affected population considering the 1811 seismic crisis scenario.

Parish	1811 seismic intensities	Dwellings for each grade of damage								Affected population	
		0		1 and 2		3		4 and 5			
		%	Number	%	Number	%	Number	%	Number	%	Number
Pilar	VIII	2 to 5	5 to 15	14 to 35	43 to 112	26 to 48	83 to 152	12 to 59	38 to 186	60 to 85	390 to 551
Ajuda	VIII	2 to 5	6 to 16	14 to 34	46 to 110	24 to 49	80 to 160	12 to 60	41 to 197	61 to 84	420 to 576
Remédios	VIII	2 to 6	6 to 18	15 to 35	50 to 113	24 to 48	79 to 155	12 to 58	39 to 190	60 to 83	596 to 823
Santa Bárbara	VIII	2 to 6	6 to 17	16 to 38	48 to 114	27 to 45	81 to 135	11 to 55	33 to 164	56 to 82	494 to 722
Sete Cidades	VIII	2 to 6	8 to 22	18 to 48	62 to 166	35 to 38	122 to 132	8 to 45	29 to 158	46 to 80	395 to 687
Feteiras	VIII	2 to 6	11 to 32	17 to 33	87 to 176	22 to 48	116 to 253	12 to 59	65 to 311	61 to 81	1039 to 1388
Santo António	VIII	3 to 8	17 to 49	21 to 38	133 to 248	24 to 43	155 to 278	11 to 53	70 to 341	54 to 77	1082 to 1538
Mosteiros	IX	1 to 2	5 to 12	6 to 15	41 to 95	14 to 29	89 to 182	54 to 79	337 to 492	54 to 82	643 to 981
Candelária	IX	1 to 2	4 to 10	8 to 18	34 to 78	16 to 22	70 to 98	57 to 75	250 to 328	57 to 79	679 to 937
Ginetes	IX	1 to 2	4 to 9	7 to 15	33 to 73	14 to 23	69 to 116	60 to 79	300 to 392	60 to 83	764 to 1049

for each seismic intensity by the EMS-98, it was estimated the total number of houses that might be affected and their respective grades of damage (Table 5). If the whole area is affected by a seismic event with intensity IX, 57% (2480) to 77% (3350) of the dwellings will partially or totally collapse and 15% (652) to 25% (1088) will need to be rehabilitated. In such a scenario, considering the 2001 census and the average of inhabitants per house for each parish, 82% (9372) to 92% (10 515) of the population will be affected (Table 5).

The application of this expedite method allows to create different scenarios that can be used to mitigate the seismic risk. As an example, it was studied the present-day impact of an event similar to the one that occurred in 1811, related with the seismic swarm that accompanied a submarine volcanic eruption, a few miles west of S. Miguel Island. In this situation three parishes (Candelária, Ginetes and Mosteiros) become affected with intensity IX (EMS-98) while the remaining area face intensity VIII (Table 6). The obtained results show that 28% (1202) to 63% (2759) of the dwellings will partially or totally collapse and 22% (944) to 38% (1661) will need to be rehabilitated. Under these circumstances 57% (6502) to 81% (9252) of the population will be affected.

5 Conclusions

Taking into account historical records and instrumental seismic data it is clear that seismic hazard at S. Miguel Island is considerably high and justify the application of expedite methods to develop scenarios useful for risk mitigation. A major earthquake should be expected to occur in a near future and appropriate preventive measures need to be implemented to minimize its impact.

Dwellings in the Sete Cidades area were classified according to their vulnerability taking into account the criteria defined by the European Macroseismic Scale 1998. A detailed field survey allowed to verify that from a total of 4351 houses, around 76% belong to class A, 17% to class B, 7% to class C and 0.1% to class D. This fact emphasizes the overall high vulnerability of the dwellings and constitutes an important fragility that should be inverted through the application of appropriate political measures.

The obtained data was used to create different scenarios for emergency planning considering the percentage of damages estimated for each seismic intensity, as it is proposed by the EMS-98. The Sete Cidades case studied allowed concluding that if the entire region faces a strong earthquake, seismic intensities can reach at least IX (EMS-98) and, therefore, a huge level of damages will occur. More than 50% of the houses may be totally or partially destroyed and between 6500 to 10 500 people will be directly affected. Such degree of destruction and the number of deaths, injured and dislodged people will cause an important social and economic disruption that can prevail for several years.

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